MECHANICAL PROPERTIES AND FAILURE BEHAVIOUR OF *GIGANTOCHLOA SCORTECHINII*

H Hamdan[1,*], UMK Anwar[1], A Zaidon[2] & M Mohd Tamizi[1]

[1]*Forest Research Institute Malaysia, 52109 Kepong, Selangor Darul Ehsan, Malaysia*
[2]*Faculty of Forestry, Universiti Putra Malaysia, 43400 Serdang, Selangor Darul Ehsan, Malaysia*

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HAMDAN H, ANWAR UMK, ZAIDON A & MOHD TAMIZI M. 2009. Mechanical properties and failure behaviour of *Gigantochloa scortechinii*. The physical and mechanical properties of bamboo have been widely studied but information of these properties at the nodes is still lacking. The presence of node in a bamboo split may affect the mechanical strength of the material. To enable usage of bamboo in a longer length, understanding the mechanical properties and behaviour of the bamboo at the node is crucial. This study used 4-year-old *Gigantochloa scortechinii* bamboo. The physical and mechanical properties at the nodal and internodal sections of the bamboo split were tested in green and air dry conditions. The orientations of the bamboo splits with the periphery of the bamboo split oriented facing downwards (referred to as compression) and facing upwards (referred to as tension) were taken into consideration during the mechanical test. Results suggested avoiding orientating the bamboo splits with the peripheral skin positioned at the bottom as it reduced the mechanical properties. The failure behaviour of bamboo splits at the node and internode were evaluated and compared.

Keywords: Node, internode, bamboo splits

HAMDAN H, ANWAR UMK, ZAIDON A & MOHD TAMIZI M. 2009. Ciri mekanik dan kegagalan buluh *Gigantochloa scortechinii*. Ciri fizikal dan mekanik buluh banyak dikaji tetapi maklumat tentang ciri buluh pada buku masih berkurangan. Kehadiran buku dalam buluh bilah boleh mempengaruhi kekuatan mekaniknya. Agar buluh yang lebih panjang dapat digunakan, pemahaman tentang ciri mekanik dan kelakuan buluh pada buku amat penting. Kajian ini menggunakan buluh *Gigantochloa scortechinii* berusia 4 tahun. Ciri-ciri fizikal dan mekanik pada buku dan ruas buluh bilah diuji dalam keadaan basah dan kering udara. Orientasi buluh bilah dengan kulit di atas (dirujuk sebagai tekanan) dan kulit di bawah (dirujuk sebagai tegangan) diambil kira semasa ujian dijalankan. Keputusan mencadangkan supaya buluh bilah tidak digunakan dengan kulitnya di bawah kerana ia akan mengurangkan ciri mekanik buluh. Kegagalan buluh di buku dan ruas dinilai dan dibandingkan.

INTRODUCTION

Utilization of bamboo has now progressed from traditional to structural such as composites and advanced material. It no longer limits its usage in round form but has been converted into splits and strips. Split refers to longitudinal split bamboo culm while strips refer to culm with the epidermis and inner culm wall removed. Bamboo in split form behaves more like solid wood (Gnanaharan *et al.* 1994). Advancement in the usage of bamboo requires further understanding of the material such as the effect of node on mechanical properties. The presence of node reduces the uniformity and elasticity of bamboo. The disposition of nodes in bamboo may not be very important from the practical point of view. However, it seems useful to know the effect of nodes from the point of view of testing (Sekhar & Bhartari 1960). Janssen (1981) found that the effect of nodes in round bamboo culm was not significant for the mechanical properties although anatomically the fibres were truncated at the nodes. However, the data on physical and mechanical properties on the effect of node in *Gigantochloa scortechinii* have yet to be documented. The nodes present along the culm height generally have higher density than those of the internodes due to lower number of parenchyma as well as lower moisture content and volumetric shrinkage (Khabir *et al.* 1995).

*E-mail: hamdan@frim.gov.my

Bamboo behaves similar to wood whereby the mechanical properties increase with decrease in moisture content (Hamdan 2004). Suzuki (1950) reported that the difference in strength between air-dried and green bamboo is relatively small. Sekhar *et al.* (1962) further concurred that the ultimate bending stress of dried bamboo is 1.5 times that of green bamboo. The mechanical properties of air-dried bamboo strips and splits of *G. scortechinii* from the internodes do not differ significantly (Anwar *et al.* 2005). Bamboo possesses excellent mechanical properties which are correlated with the density. Liese (1985) indicated that these depend mainly on the fibre content and therefore vary considerably within the culm and between species.

It is important to avoid failure of a material in utilization for security and safety reasons. As such, a failure criterion must be established by emphasizing that the stress level is held within the stress–strain linear range (Bodig & Jayne 1982). In bamboo, there is no spontaneous failure when tested for bending (Liese 1988). However, when round culms were tested for bending, two types of failures were identified, i.e. splitting and local crushing (Chung & Yu 2002). The splitting, however, mainly occurs in dry culms while in green bamboo the failure is more localized. The compressive stress occurring in the bamboo samples in split form tends to concentrate on the periphery of the fibre bundle (Liese 1988). It was also observed that upon further loading, the accumulated stress causes tangential and/or longitudinal shear along the fibre matrix resulting in failure of the bamboo splits.

This paper reports the mechanical properties of 4-year-old splits of *G. scortechinii* culm when tested in green condition. *Gigantochloa scortechinii* is the most popular bamboo species and is abundantly found in Peninsular Malaysia. The mechanical properties evaluated were modulus of elasticity (MOE) and modulus of rupture (MOR) in static bending and compression parallel to the grain at the node and internode of the bamboo splits. The behaviour and failure characteristic of the bamboo were also evaluated.

MATERIALS AND METHODS

Preparation of materials

The 4-year-old *G. scortechinii* bamboo was extracted randomly from selected clumps with diameters ranging from 10 to 15 cm. The bamboo culms were cut at about 150 mm above the ground level and only 12 m were taken while the remaining upper portion discarded. It was subsequently subdivided into three equal portions along the height of the culm (approximately 4 m at each portion) and labelled as basal, middle and top, and the ends coated. Each portion was split longitudinally into two halves containing both nodes and internodes (referred to as location). The green samples were all tested within five days of felling while another set was air dried under shed and conditioned in a conditioning room at 65% relative humidity and about 12% moisture content (MC) for about three days prior to testing.

Physical and mechanical properties

Samples of 20 × 20 mm × thickness were taken near the failure point of the specimens for determination of MC and density. The procedures used for the determination of MC were elaborated in Hamdan (2004) and the IS 6874 (Anonymous 1972). A total of 15 replicates were evaluated for each parameter. For the static bending tests, the split samples of 300 × 20 mm × culm wall thickness were obtained from the basal portion (locations 4 and 5), middle portion (locations 14 and 15) and top portion (locations 23 and 24) comprising both nodes and internodes. A total of 15 replicates each were prepared. The protruding diaphragm at the nodes was first removed so as to position the node centrally when the cross head was lowered prior to testing. An Instron testing machine was used, and testing was performed with central loading and a cross-head speed of 0.65 mm s^{-1} for bending. The span followed the method by Gnanaharan *et al.* (1994). During testing, the samples were orientated with the peripheral skin at the top and the other set of samples with the peripheral skin positioned at the bottom. For compression test, the samples were cut into 10 × 40 mm × culm wall thickness in accordance to Janssen (1981). The samples were also tested using the Instron machine at a cross-head speed of 0.65 mm s^{-1} .

Failure characteristics

The study involved analysing the behaviour and stress–strain characteristics of bamboo split obtained from static bending (samples with the peripheral skin at the top). Bamboo samples were tested for compression parallel to the grain. The failed samples were evaluated only at macro level which involved visual observation and the failure mode was recorded according to Bodig and Jayne (1982).

Statistical analysis

The data were analysed using the Statistical Analysis System software (SAS). Regression analysis was performed to determine the relationship between MC and position along the culm height. The mechanical properties were then adjusted to a constant MC of 90% (this being the mean MC of nodes and internodes as in Table 1). These properties and density were analysed using the analysis of covariance (ANCOVA).

RESULTS AND DISCUSSION

Physical properties

The trend for MC with height was the same for both node and internode, whereby it decreased although the ANOVA results showed no significant difference (Table 1). The highest MC was recorded at the basal portion of the internode while the lowest was at the top portion of the node. A similar trend was also reported by Khabir *et al.* (1995) in *Dendrocalamus hamiltoni*. Comparatively, the MC recorded here was lower than that reported by Anwar *et al.* (2005) although the samples were collected from the same location. Liese (1980) reported that moisture between culm may differ with season. The higher MC at the internode could be influenced by the anatomical structure of bamboo. There is a higher ratio of vascular bundles to parenchyma present here as compared with the node.

The mean density values in Table 1 showed an inverse trend with MC, whereby the values increased with culm height. There was no significant difference in density between the node and internode at three different heights of the green bamboo. The mean MC and density for air-dried samples were about 11% and 0.65 g cm^{-3} respectively (results not shown). This trend could be associated with the presence of abundant vascular bundles (Liese 1987, Abd Latif & Mohd Tamizi 1992) coupled with the presence of high amount of silica (Espiloy 1983). The high density recorded was due to the high concentration of truncated vascular bundles present at the nodal area. Khabir *et al.* (1995) reported a significant difference in MC between node and internode; the latter being about 20% lower.

The regression analysis result showed a strong linear relationship between moisture content and position along the culm for the internode with

Table 1 Mean moisture content and density of green *Gigantochloa scortechinii* nodes and internodes at three height positions taken from samples after mechanical tests

Position	Moisture content (%)		Density (g cm^{-3})	
	Node	Internode	Node	Internode
Basal	96.64 a	100.34 a	0.58 a	0.52 a
	(9.48)	(8.00)	(0.05)	(0.09)
Middle	87.39 a	91.86 a	0.63 a	0.57 a
	(17.40)	(12.23)	(0.07)	(0.05)
Top	81.37 a	82.7 a	0.66 a	0.63 a
	(13.01)	(13.52)	(0.05)	(0.07)
Mean	88.47	91.63	0.62	0.57
	(13.3)	(11.25)	(0.06)	(0.07)

Values in parentheses are standard deviations. Means followed by the same letter in the same column are not significantly different at the 0.05 probability level.

r^2 = of 0.91 (Figure 1). However, the coefficient of determination recorded for node was only 0.64.

The negative relationship indicated decrement in MC with culm height which was more pronounced in the internode. This could probably be due to the anatomical structure of bamboo at the internode. However, the same explanation could not be applied for MC at the node. This is probably because the relatively lower MC observed at the node is influenced by the presence of low number of parenchyma that serves as sites for water storage (Abd Latif & Mohd Zain 1992) as well as the truncated and disarray orientation of fibre bundle observed at the node (Hamdan 2004).

Mechanical properties

Table 2 shows results of the adjusted mean mechanical properties (average of both orientations) obtained from quantitative analysis tested in green and air-dry conditions. The mean mechanical properties generally increased with height in both the nodes and internodes. This conforms to studies conducted by other researchers (Mansur 2000, Anwar *et al.* 2005) who showed that mechanical properties were greater at the top portion when nodes and internodes were tested in dry condition (below fibre saturation point).

Further statistical analysis was carried out on the effect of MC on the mechanical properties of green bamboo when the MC was adjusted to 90%. It is interesting to note that when the MC was adjusted, mechanical properties of the green bamboo split decreased with height. This shows that MC influences the properties quite significantly especially for MOE. While position did not influence the MOR and compression in both node and internode of green and air-dried samples, the MOE, however, was affected by position and condition.

The values for MOE and MOR at the internode were relatively higher than the node (Table 3). This is reflected in the statistical analysis, whereby the MOE between node and internode was significantly different but not for MOR. When the results were further compared between locations but same orientation, only MOR tested in compression was not significantly different.

When MOE values were measured with different grain orientations, they showed similar trend in contrast to those of MOR values. This is mainly contributed by the anatomical structure of the bamboo, whereby the dense vascular bundle at the periphery provides resistance to stress, giving rise to the higher value. The influence of position along culm height was also reported by Limaye (1952). He found that the MOE of bamboo tested in green condition markedly increased

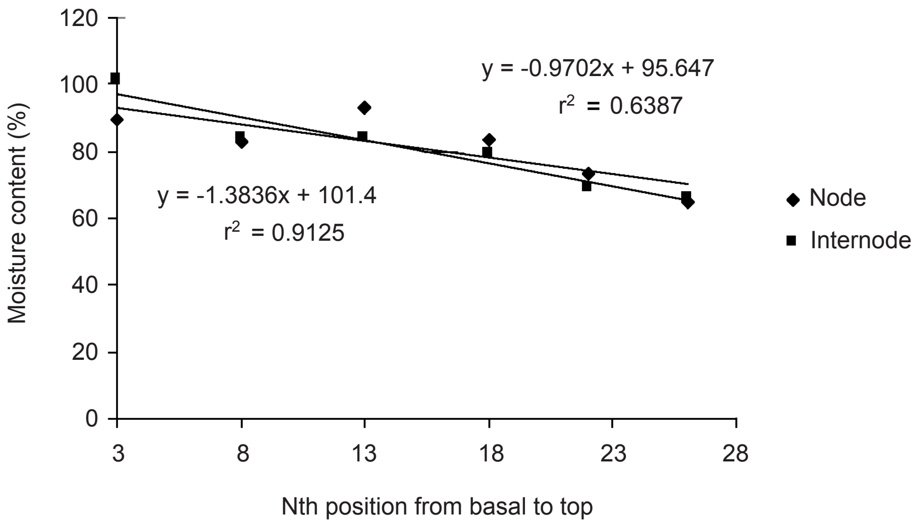

Figure 1 Moisture content of green 4-year-old *G. scortechinii* at the node and internode along the culm height

Table 2 Mechanical properties of *G. scortechinii* bamboo split at node and internode at three height positions

Position	Node			Internode		
	Green		Air dried	Green		Air dried
	Mean	Adjusted	Mean	Mean	Adjusted	Mean
			MOE (N mm^{-2})			
Basal	6969 (1507)	7787 a	10647 a (2509)	10036 (1335)	9676 a	13442 a (1712)
Middle	7254 (1761)	7462 ab	12048 a (2455)	9005 (2131)	8117 b	15164 b (2570)
Top	8116 (1979)	6883 b	12009 a (2629)	9931 (2870)	7948 b	15032 b (2914)
			MOR (N mm^{-2})			
Basal	84.4 (20.7)	82.4 a	123.3 a (29.3)	85.8 (12.4)	81.5 a	151.2 a (24.5)
Middle	79.9 (17.7)	79.9 a	135.0 a (32.3)	92.9 (23.7)	82.4 a	149.6 a (35.5)
Top	87.4 (22.3)	74.5 a	129.2 a (31.0)	97.6 (20.7)	80.4 a	155.8 a (32.7)
			Compression (N mm^{-2})			
Basal	29.8 (4.7)	31.3 a	85.6 a (10.2)	34.2 (6.3)	39.3 a	73.9 a (5.9)
Middle	28.6 (4.8)	30.7 a	70.7 b (10.2)	34.7 (5.3)	37.0 a	73.5 a (6.8)
Top	31.5 (3.9)	29.2 a	72.3 b (17.2)	39.6 (6.2)	36.7 a	76.0 a (10.12)

Values in parentheses are standard deviations; n = 15; MOE = modulus of elasticity; MOR = modulus of rupture.
Means followed by the same letter within a column are not significantly different at the 0.05 probability level.

with height. When comparing between node and internode with the same orientation, the results again consistently recorded significantly higher values at the internode except for MOR tested in compression. This implies that to maximize the stiffness and strength during usage, the node or internode sections of bamboo splits should be orientated in compression. For compression parallel to the grain test, the MOR decreased with height. However, this trend reversed when it was adjusted to a fixed MC of 90% although the difference was not significant. This indicates a strong influence of moisture on the bamboo and when the MC is constant other factors may also contribute.

The results can be explained by the strong influence of the anatomical structure of bamboo on mechanical properties. Bamboo density has a close relation with vascular bundle and ground tissue percentage, which according to Janssen (1981), Espiloy (1987) and Widjaja and Risyad (1987) have an important role in the development of the mechanical properties of bamboo.

Failure behaviour

The failure trend in bamboo splits with node present consistently originated from the node scar located at the tension side where the diaphragms were once present. Upon further loading, it initiated a lateral shearing failure while reaching its ultimate stress (Figures 2a and b). Comparatively, for the internode, the failure mode also showed a transverse failure on the tension side with some lateral shear. Little creases also appeared on the peripheral

Table 3 Bending properties of *G. scortechinii* between location and orientation

Position	MOE (N mm^{-2})			MOR (N mm^{-2})		
	Green		Air dried	Green		Air dried
Between location	Mean	Adjusted	Mean	Mean	Adjusted	Mean
Node	7418 (1790)	7395 a	11479 a (2752)	82.05 (20.13)	78.92 a	128.99 a (30.71)
Internode	9425 (2247)	8555 b	14546 b (2542)	90.68 (23.07)	81.43 a	152.21 b (30.9)
Between orientation						
Compression	8619 (2343)	7958 a	13172 a (3055)	97.15 (19.02)	91.66 a	136.82 a (32.42)
Tension	8210.55 (2167)	7980 a	12892 a (3098)	75.42 (19.34)	68.40 b	144.82 a (29.58)
Between location but same orientation						
Node-compression	7522 (1874)	7395 a	11432 a (2438)	95.26 (16.68)	89.44 a	115.85 a (31.17)
Internode-compression	9715 (2266)	8520 b	14912 b (2660)	99.03 (20.98)	93.88 a	157.79 b (32.39)
Node-tension	7314 (1716)	7418 a	11529 a (3047)	68.84 (13.34)	63.95 a	142.90 a (30.76)
Internode-tension	9127 (2213)	8542 b	14180 b (2399)	82.15 (22.17)	73.06 b	146.63 a (28.75)

Values in parentheses are standard deviations; n = 15.
Means followed by the same letter within a column are not significantly different at the 0.05 probability level.

surface indicating stress line at the compression side (Figures 2c and d). Bodig and Jayne (1982) explained that this type of failure usually appears at loads less than the ultimate. However, tension breaks will eventually appear so that both types of failures are present with completion of the test.

In compression, the bamboo under uniaxial load showed different failure behaviours for the node and internode. At the node, the crack tended to originate from the bottom end and sheared perpendicularly upwards but terminated below the nodal area (Figure 2e). However, for the internode, it began with crushing of the culm wall from the bottom end and shear splitting in the middle upwards that propagated above the crushed area upwards (Figure 2f).

Kisser and Steininger (1952) recorded the formation of creases on the compression side of wood samples subjected to static bending at 50% of the load at which the macroscopic crease occurred. In bamboo, creases appeared on the compression side after about 80% of the stress load. This could be contributed by the vascular bundle with thick polylamellated layer of fibre and high percentage of parenchyma present in bamboo complements that are able to resist stress.

On the tension side, failure of internode splits occurred at about one-third of the culm wall thickness. This would mean that as the transverse failure was propagated at the opposite of the loaded side, no spontaneous fracture occurred as the crack became deflected in the direction of the weak matrix of the fibre bundle.This is the classic Cook–Gordon crack-stopping mechanism (Gordon 1976). While at the node, anatomically the failure further progressed laterally in shear which occurred along the weak fibre matrices. An illustration of the failure characteristic at the node (abrupt) and that of the internode is graphical shown in Figure 3.

Kappel *et al.* (2004) reported that the presence of node diaphragm in round bamboo seems to prevent failure due to cross-sectional flattening. The failure in bending of bamboo is not actually

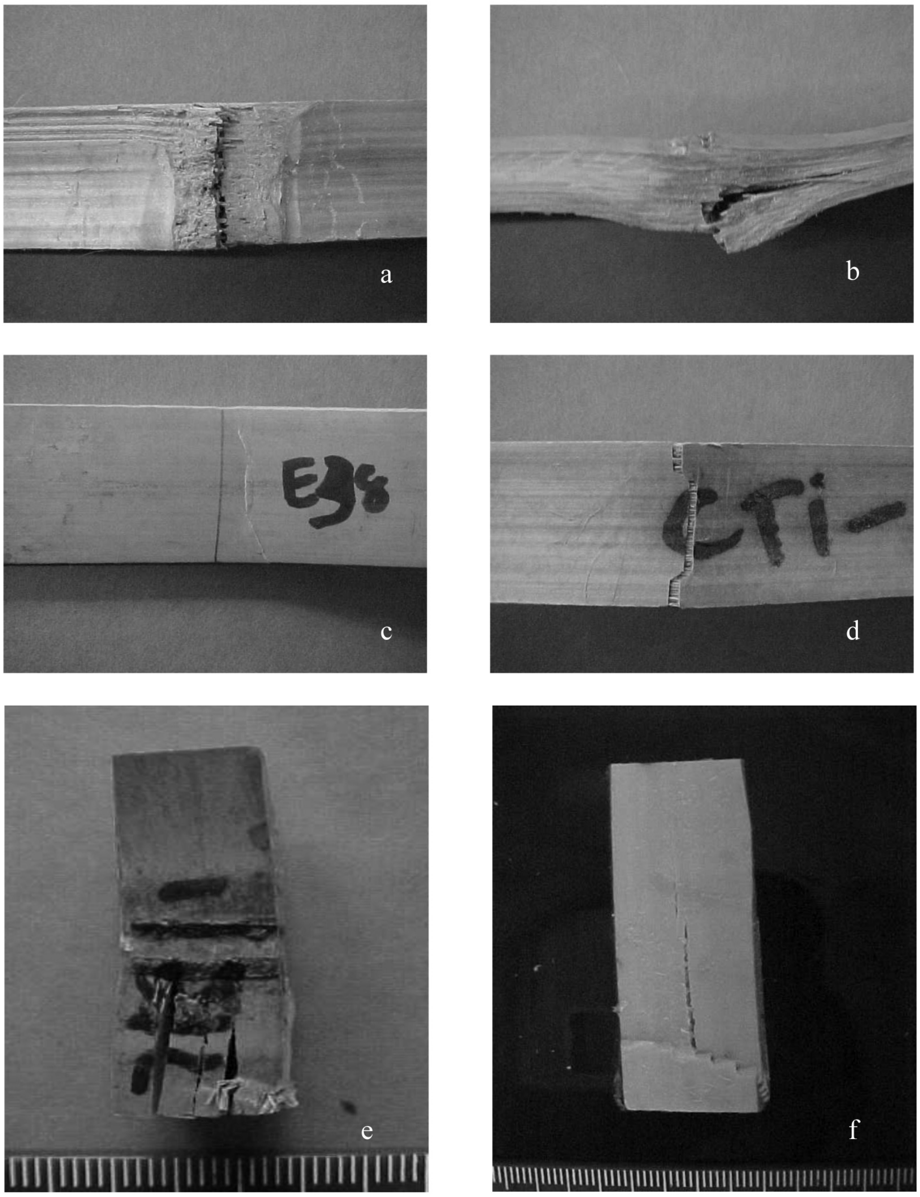

Figure 2 Failure mode and characteristics of bamboo splits: bending test for node (2a, b) and internode(2c, d); compression test for node and internode respectively (2e, f)

totally failure which is due to its strong fibre structure. This quality of bamboo gives an opportunity to repair or replace the component that has failed.

CONCLUSIONS

The results of this study showed that MC for both node and internode sections of *G. scortechinii* culm decreased with height. The reduction in strength at the node is probably contributed by the shorter, thicker and forked fibres and the random orientation of vascular bundles that truncated towards the diaphragm. It is imperative that the use of bamboo should avoid orientating the bamboo splits with the periphery positioned at the bottom as it may reduce the mechanical properties. When using bamboo that would involve span, it is suggested that the periphery of the bamboo split be positioned facing upwards to obtain optimum strength and stiffness. Similarly, this also applies when node is present.

The failure behaviour at the node is characterized by spontaneous break at the diaphragm scar during bending and end splitting during compression. The trend does not follow for internode as failure occurs quite gradually.

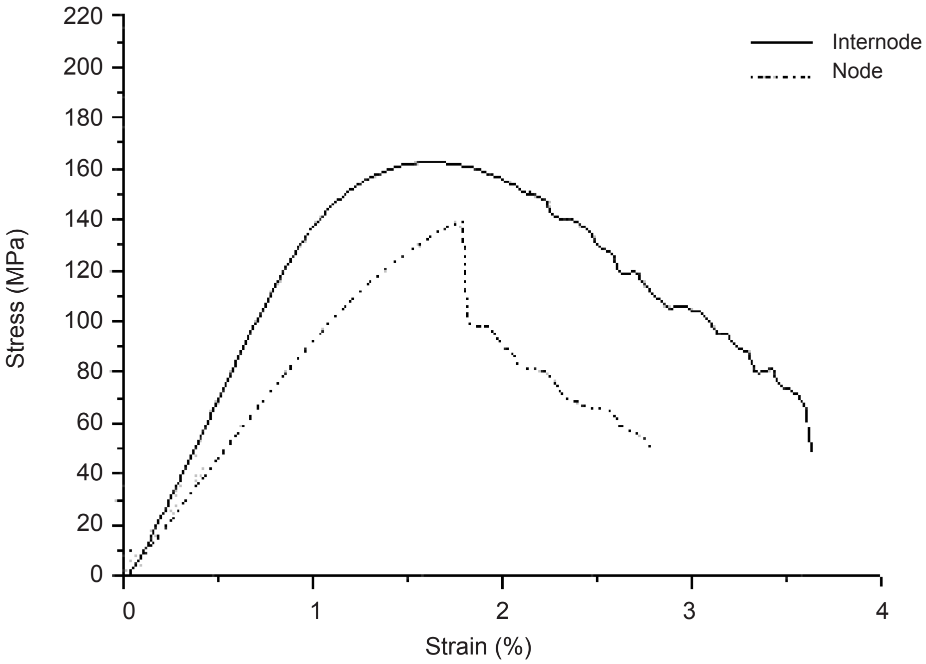

Figure 3 Typical failure behaviour of bamboo splits at node and internode during bending test

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